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AN EVALUATION OF THE USES AND MORPHOLOGY OF ATMOSPHERIC FLUIDIZED BED COMBUSTION WASTES FROM CFB SUMMERSIDE AFBC BOILERS

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E.E. Berry*, E.J. Anthony** and D.P. Kalmanovitch***

ABSTRACT

The literature on FBC solid wastes has been critically evaluated and solid wastes from Canada's first atmospheric fluidized bed combustion (AFBC) boilers at the Canadian Forces Base Summerside, Prince Edward Island have been investigated in order to determine possible uses for AFBC wastes. Scanning electron microscopy (SEM), electron microprobe and chemical and physical tests were employed to determine the suitability of the material for pollution control, construction and other uses. SEM and ancillary techniques have shown that the chemical and physical properties of the bed material and the elutriated streams are significantly different. Agricultural use, pollution control, soil stabilization (where freezing and thawing are not significant problems), asphaltic concrete and specialized construction applications such as low strength backfill appear to be potential uses for FBC solid wastes.

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ÉVALUATION DES UTILISATIONS ET DE LA MORPHOLOGIE DES RÉSIDUS DE COMBUSTION EN LIT FLUIDISÉ ATMOSPHÉRIQUE (CLFA) PROVENANT DES CHAUDIÈRES CLFA À LA BASE MILITAIRE DES FORCES CANADIENNES DE SUMMERSIDE

par

E.E. Berry*, E.J. Anthony** et D.P. Kalmanovitch***

RÉSUMÉ

On a effectué une évaluation critique de la littérature sur les résidus de la CLF ainsi qu'une étude des résidus solides des premières chaudières à combustion en lit fluidisé atmosphérique situées à la base militaire des Forces canadiennes de Summerside à l'I.-P.-É. Ces travaux avaient pour but de déterminer les utilisations possibles pour les résidus de CLFA. On a utilisé, pour ce faire, des procédés d'analyse au moyen du microscope électronique à balayage (MEB) et de la microsonde électronique et enfin, des analyses chimiques et physiques afin de déterminer si ce matériau est approprié au contrôle de la pollution, à servir de matériau de construction ou à d'autres usages. Les résultats des analyses du MEB et des autres techniques accessoires ont indiqué que les propriétés chimiques et physiques des matériaux du lit et des matériaux provenant des canalisations éluées diffèrent de façon significative. Les résidus solides de CLF semblent avoir des utilisations possibles dans les domaines suivants: l'agriculture, le contrôle de la pollution, la stabilisation des sols (où le gel et le dégel ne présentent pas un problème sérieux), le béton asphaltique et enfin, ils pourraient servir à des applications spécialisées dans les matériaux de construction.

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1. INTRODUCTION

Fluidized bed combustion (FBC) is being developed for more efficient generation of steam for industrial use or thermal power as well as reduced acidic gaseous emissions. FBC boilers are in the early stages of commercial applications in most western nations and are widely used in China.

In a report to the Parliament of Canada (1), the Special Committee on Alternative Energy and Oil Substitution identified fluidized bed combustion technology as offering:

> "... the best approach to minimizing emissions of sulphur and nitrogen oxides from coal-fired boilers and for allowing the efficient combustion of a wide variety of low grade fuels."

A fluidized bed consists of a mass of granular particles through which an upward flow of air or gas is passed with sufficient velocity so that the drag force acting on the particles is equal to the gravitational force holding the particles down. At this point the particles will lift and be separated and the bed will expand upwards as the particles become suspended in the gas stream. This state is known as fluidization and the bed demonstrates many of the properties of a liquid, having a flat surface and responding in the same way as a liquid for operations involving stirring and pouring. A fuel can be introduced into or on the fluidized bed resulting in intimate contact with the bed material and the combustion air passing through. This allows combustion to occur at temperatures below the ash fusion point of most solid fuels (1000°C) and the agitated bed particles demonstrate very good heat transfer characteristics for boiler operation.

For high sulphur fuels, an appropriate bed material for atmospheric pressure fluidized-bed combustion (AFBC) results from using limestone as the sorbent.

The combustion heat calcines the calcium carbonate to calcium oxide which reacts with the oxides of sulphur, formed during combustion of the coal, to form calcium sulphate. This reduces the emission of sulphur oxides to the atmosphere. For optimum SO_x absorption the temperature of the bed is typically controlled between 815°C and 870°C. Limestone is fed to the bed to maintain the desired level of SO_x absorption. Spent bed material is removed at

a controlled rate by a bed drain and fine particulates are removed from the exhaust gases by dust collecting devices such as cyclones or baghouses.

It has been recognized that, under some circumstances, disposal of the residues may cause pollution of soil and water. In general the following concerns have been expressed with regard to disposal of AFBC waste products:

- generation of high pH levels in soils and water courses;
- discharge of dissolved solids (TDS) to water courses;
- leaching of calcium and sulphate to groundwaters;
- trace element leaching to groundwaters;
- thermal activity of the quicklime component on exposure to water;
- release of trace organic components to the environment.

If the advantages of FBC are to be realized in practice, without introducing a risk of ground or water pollution, it is necessary to establish environmentally acceptable means to dispose of the sulphated solid residues. In this respect it would be valuable if AFBC wastes could be used as secondary resources in the construction or the manufacturing industries.

The departments of Energy, Mines and Resources Canada (EMR) and National Defence co-sponsored the installation of two 18 t/h steam boilers at CFB Summerside, Prince Edward Island. The installation has been designed to burn a variety of fuels including relatively high-sulphur (5%) coals from Cape Breton, using New Brunswick limestone as a bed material (2).

This report summarizes the findings of a study of the potential uses of AFBC residues. The principal objective of the study was to examine potential uses for the solid residues from the plant at Summerside. The second objective was to review current knowledge of uses for AFBC residues to provide information for similarly planned AFBC installations in Canada.

To meet these objectives the project was conducted in four parts:

- The published literature on the nature, properties and utilization of AFBC residues was examined and critically reviewed.
- An examination was made of information obtained from other workers in Canada on the nature of residue samples taken from the Summerside plant.

- Samples of residues from the Summerside plant were examined in the laboratory and their potential as sources of construction materials was considered.
- The data were then considered in terms of the construction practices and economic factors specific to Prince Edward Island and recommendations for action were formulated. In addition the data were considered in the context of possible AFBC development elsewhere in Canada and more general recommendations were developed.

It is not intended to present either the detailed review of the previous literature or a complete record of the data from the laboratory study. For these items the reader is referred to the original reports (3,4). Rather, it is intended to present an overview of the subject matter and the conclusions drawn from the study together with some supporting data on the microstructure of solid wastes from CFB Summerside.

2. LITERATURE REVIEW

Although the technology of fluidized bed combustion was developed in Germany as early as the 1920's, only recently has attention been given to the nature, disposal and possible use of the solid residues from FBC boilers.

Reports from previous studies of the nature and possible uses of materials from a number of FBC installations in the United States are available from four projects (5-9). Bennett et al. (10-14) report on potential agricultural applications. The implications of previous work with regard to the possible use of AFBC in Canada has been the subject of three reports (15-17). The present investigation is the first to examine AFBC wastes from a Canadian source for the specific purpose of establishing their potential as usable resources.

A wide range of applications for AFBC residues have been considered in the literature. However, it was concluded that the following are the most practical:

- agriculture;
- lime substitute in acidic waste neutralization;
- waste stabilizing agent in lime/pozzolan systems;
- low strength backfill applications (with or without Portland cement);

- soil stabilization and soil cementing;
- asphaltic concrete aggregate.

3. THE NATURE OF AFBC RESIDUES

As by Sun et al. (8) the nature of fluidized bed wastes depends on a multitude of interacting variables. Consequently many materials having different properties can result from different FBC installations or from the same installation when different fuels are burned or operating conditions are changed. A typical material flow for an AFBC system is shown schematically in Fig. 1.

In most installations, AFB combustion of coal in a limestone bed produces two distinct solid residues:

- dry, partially sulphated calcined lime particles of a relatively coarse size that are discharged from the bed drain (termed bed drain material in this report);
- dry, fine particulate matter comprising sorbent and ash that is collected by the dust control system (baghouse or other device) used to clean the exhaust gases prior to their being discharged to the atmosphere (termed baghouse ash in this report).

In some instances, such as the Summerside installation, these two waste streams are removed from the plant as a mixed residue (termed silo ash in this report).

Except for chemical components that might be volatilized and discharged with the combustion gases, the residues from AFB combustion can be expected to comprise solids or mixtures of solids formed from the chemical components introduced with the limestone and the coal.

Collins (18) and Minnick (19) have reported the results of X-ray diffraction examination of residues from a number of AFBC sources. From their data it may be concluded that fluidized bed residues are composed of:

- $CaSO_4$ (anhydrite)
- CaO (unsulphated lime)
- $CaCO_3$

- MgO
- silicates and aluminates (derived from clays)
- SiO_2 (from sand or quartz impurities)
- Fe_2O_3 (or Fe_3O_4)
- ferrites and other iron compounds
- minor and trace elements in various states of chemical combination

It has been reported that AFBC residues, particularly bed drain materials, are heterogeneous at the level of individual particles. There is evidence that particles of bed drain comprise a core of unreacted CaO surrounded by a coating of $CaSO_4$ (20, 21). The morphology of the solid residues from the CFB Summerside boilers is discussed in greater detail in Section 4.1.1 "Microstructure of Fluidized Bed Material".

4. LABORATORY EXAMINATION OF AFBC WASTES FROM CFB SUMMERSIDE

Samples of bed drain, baghouse ash and silo ash from the Summerside plant were examined in the laboratory for chemical, physical and engineering properties. The physical examination was carried out by SEM.

4.1 CHEMICAL PROPERTIES

Samples from the Summerside plant were analyzed by Constable (22). Data from these analyses are given in Table 1. It is clear from these data that some separation of the constituents of the original materials occurs between the bed drain and the dust collector discharges. The bed drain materials appear to be derived from the limestone and the products of sulphation whereas the coal-ash components are collected in the baghouse.

Alkalinity, reactivity and total sulphur data for the Summerside samples were used to estimate the amount of CaO in each solid stream (Table 2), and to calculate comparative neutralization relationships between the residues and lime (Table 3).

The differences between the data determined by the ASTM C 400-64 method and those reported by Constable (22) indicate that the rate of reaction of AFBC residues with acidic solutions is very much slower than that for chemical lime. This would cause the ASTM test, which is designed for relatively

pure lime, to give low results unless an extended reaction period was used. The data from Constable are consistent with the approximate $CaO/CaSO_4$ proportions calculated above from total sulphur analyses. The relatively slow rate of reaction of the bed drain material is consistent with the presence of a coating (probably $CaSO_4$) on the particle surfaces.

From the above considerations, an approximation of the phase distribution of the principal components of the residues may be made as shown in Table 4.

It was concluded that the AFBC residues have an equivalent lime content ranging from 30 to 40%, however, in a form that is much less readily reactive with acidic sources than chemical lime. None of the chemical data indicate any unusual properties that would distinguish the Summerside materials as being markedly different from those examined by others.

It is evident that the solid components formed in the fluidized bed are quite different from the typical ashes from conventional combustion of coals. In general, conventional pulverized fuel ash (fly ash or PFA) comprises chemical compounds of the major oxide components in the form of glassy spheres with some crystalline constituents such as mullite, hematite, magnetite and quartz (23). Because the fluidized bed operates at lower temperatures than those typically reached in a pulverized coal flame, melting of the inorganic constituents does not occur. Without the opportunity for ion transport through a molten phase, mixing of components is greatly restricted and the formation of glasses is retarded.

The distinction between these two classes of combustion residues is of considerable importance with regard to utilization of AFBC wastes because most of the proven applications claimed for conventional combustion ashes depend greatly upon their morphology and glassy nature (24). Failure to consider these distinctions has led some previous authors to suggest uses for AFBC wastes that are probably inconsistent with their unique properties (16).

4.1.1 Microstructure of Fluidized Bed Material

The material employed in this study was from two AFBC boilers at CFB Summerside. The sulphur sorbent was Havelock limestone from New Brunswick. Pilot plant studies have shown it to be a moderately good limestone for sulphur capture (25). Detailed operating conditions of the units are given elsewhere (26), however it should be noted that the average bed temperature

was 850°C and material less than 50 μm was elutriated and captured by the baghouse.

On entering the bed the limestone ($CaCO_3$) is rapidly calcined to form porous lime (CaO). The sulphur from the coal forms SO_x species during combustion which react with the lime and the oxygen in the flue gas to form calcium sulphate ($CaSO_4$). The typical reaction may be represented as

$$CaO + 1/2\ O_2 + SO_2 \rightarrow CaSO_4$$

The reaction, though thermodynamically favourable at the temperature employed, does not go to completion for a number of reasons. Mainly blocking of the pores in the sorbent due to the formation of calcium sulphate, which has a larger molar volume than calcium oxide prevents the diffusion of gaseous reactants to the CaO in the interior of the particles. Thus, the usual utilization of limestone in an AFBC may be about 35%, leaving an excess of unreacted CaO (the normal Ca/S molar ratio employed in an AFBC is of the order of 2 to 3). It is important to note that the partial utilization is on a particle basis and that the material is an intimate mix of $CaSO_4$ and CaO. In addition, the bed material contains coal mineral matter, the extent and characteristics of which are dependent both on the origin of the coal and the operating condition of the combustor. Thus the ash from CFB Summerside contains significant quantities of shale particles (alumino silicates). These are large and are easily distinguishable from the limestone.

During combustion fine ash particles are produced from both the mineral matter and the limestone. These particles are elutriated via the freeboard and if they are larger than 50 μm they are typically captured by the cyclone and returned to the bed. The remaining particles pass to the baghouse.

Examination of the baghouse fraction of elutriated solids shows that it consists primarily of CaO, unburnt carbon and fly ash. The CaO is produced from the fragmentation of limestone particles during calcination. The calcination is endothermic and appears to result in violent fragmentation of Havelock limestone. Plate 1 shows that there are cracks in the raw limestone and it is reasonable to suppose that fragmentation will occur along these original cracks. SEM has confirmed that there is relatively little $CaSO_4$ in the baghouse material and this supports the idea that the bulk of the calcium

containing species in the baghouse results from early fragmentation of the limestone before significant sulphation can take place. If attrition of the bed material was a major mechanism for producing these fines one would expect to see more $CaSO_4$ in the baghouse. The degree of unburnt carbon present is a function of both the operating conditions and the maceral content of the coal (27). The characteristics of the fly ash particles also strongly depend on the nature of the coal.

Waste management of FBC solid material will be enhanced by knowledge of the chemical and physical properties of $CaSO_4$, CaO, coal ash and unburnt carbon. However, the predominant components in the wastes, when high sulphur fuels are employed at CFB Summerside will always be calcium sulphate and lime.

Typically, the unburnt carbon should not present significant problems. After passing through a combustion zone it is relatively unreactive as the residence time of such particles is of the order of seconds to minutes. In addition, the relatively inert carbon containing char particles are strongly diluted by the presence of fly ash and residues from the limestone so that risk of spontaneous combustion due to the char fraction during storage or removal ought to be small or negligible. The fly ash may however pose a problem because of heavy metal impurities which can be leached. However it is worth noting that except for amphoteric species, e.g., boron, aluminum, vandadium (it is interesting to note that Zn does not seem to be mobilized), the high pH of the leachate can be expected to prevent mobilization of heavy metal cations (28).

Both the lime and calcium sulphate react exothermically with moisture from the atmosphere to form calcium hydroxide ($CaOH_2$) and gypsum ($CaSO_4.2H_2O$) respectively. Since these two components are found in an intimate mix in each particle the exothermicity of bed material upon exposure to moisture will be a complex function of both the chemical properties of CaO and $CaSO_4$ and the morphology of the particles.

Analysis of Plates 2 and 3 shows that the sulphate forms a relatively dense and impermeable layer or outer shell around an inner core of lime. Thus in the first instance the properties of the sulphate will dominate the hydration reaction, and this reaction is slow under normal or ambient conditions. However, once the sulphate shell is fractured either by weathering or spalling due to chemical reactions with the sulphate or mechanical agitation, the more rapid and strongly exothermic hydration reaction of CaO to form $Ca(OH)_2$ may occur.

4.1.2 SEM and EDX Examination of Samples from CFB Summerside

Samples of waste materials produced by AFBC at Summerside have been studied by scanning electron microscopy with energy dispersive microprobe. The typical features of wastes are shown in Plates 1 to 9. Thus Plate 1 shows the porous calcined region that forms when the limestone is introduced to the bed together with cracks in the original limestone structure. Plate 2 shows the dense, highly crystalline sulphate outer shell which results upon reaction with SO_2 and Plate 3 shows that sulphated regions produce a layer around the central unreacted CaO core of the particle.

The high surface area of the CaO would indicate that rapid reaction with moisture should occur. However, this process is severely moderated by the presence of the sulphate shell which may be expected to significantly retard diffusion of moisture to the core in the first instance.

The cracks that can be seen in the sulphate shell (Plates 1 and 2) are probably due to handling of the particle but may also in part result from the quenching of the particles (from 650° to 20°C, i.e., from bed temperature to ambient conditions) when they are withdrawn from the combustor to maintain a constant bed inventory of solids. In view of the structure of the particles with the intimate mixture of $CaSO_4$ and CaO it might have been anticipated that both differences in thermal expansion coefficient and the molar volumes of hydrated species would lead to very poor freeze-thaw characteristics. Subsequently, as discussed later, the material was shown to fragment relatively easily in freeze-thaw cycling experiments in the presence of soil-cement mixes.

A number of other features were observed in the bed particles. Plate 4 shows a well formed iron rich layer (15-20 μm) in the sulphate shell of the particles. The origin of this layer is not definitely known, however other work has indicated that it is probably formed as a result of reaction between fly ash species and $CaSO_4$ (29). No sulphur was detected in this layer by energy dispersive X-ray (EDX) analysis and it seems reasonable to assume that its formation involved the emission of sulphur oxide species. This observation is consistent with other work which has shown that iron rich coals and the presence of iron salts may in some cases inhibit the sulphation reaction (30, 31). It is reasonable to assume that this layer may affect the diffusion of reactants to the sulphate layer and the calcined core of the particles.

The mineral matter observed in the bed material employing SEM and EDX was shown to consist primarily of Si and Al and was taken to be clay or shale in origin. Although it is known that the thermal treatment of clay and shale minerals (heated to 1000°C) will result in a breakdown or cause rearrangement of the crystal lattice it is difficult on a priori grounds to predict what effect this treatment will have on this material's leaching characteristics.

Plate 5 shows a particle which had been exposed to the atmosphere for several days allowing the hydration products to be observed. The structure clearly indicates that the hydration of CaO causes a significant increase in molar volume which in turn leads to cracking and fragmentation of the bed particle. Thus any particle at this stage of hydration may be expected to show very poor freeze-thaw characteristics until the hydration reaction is essentially complete. It is worth noting that the authors have observed that this material in bulk tends to form clumps or boulders upon weathering with a relatively firm outer layer or shell several millimeters or even centimeters thick. This may further retard the hydration reaction (Plates 6 and 7).

Plate 8 shows that the cyclone material is composed of char (irregular shaped particles), ash and calcined limestone particles. The size ranges typically from 10 to 80 µm. The calcined limestone particles do not appear to be the products of fragmented sulphated bed material. Thus if the particles fragment to any significant degree after sulphation these must be found either in the bed or baghouse because the Ca rich species observed are relatively depleted in S. Morphological investigation did not reveal any features which were obviously fragments of sulphated limestone particles.

Plate 9 shows that most of the baghouse material is very fine with particles less than 10 µm and that much of it is in the micron range. Again, analysis indicates that S content was low which suggests residence times in the bed are short and that sulphated bed particles do not fragment to any significant extent because the Ca species in both the cyclone and baghouse are low in S. It should be noted that the particles approach the respirable air born range.

Plates 10 and 11 show more samples of elutriated material (baghouse). The large particles are ash or char but most of the material represents elutriated calcined limestone fragments.

4.2 ENGINEERING PROPERTIES

After reviewing the previously reported work, it was concluded that the following engineering applications might be proposed for AFBC residues:

- soil modification and cementing,
- asphaltic concrete aggregate,
- aggregate in low strength Portland cement based materials.

To investigate these potential uses, laboratory tests were carried out using Summerside samples and local construction materials.

4.2.1 Soil Cementing Properties

Highway construction in P.E.I. frequently requires the use of soil-cement to stabilize non-plastic, silty sub-base soils. Although soil-cement is beneficial it has been found that reflection cracking of pavements occurs due to shrinkage of the soil-cement bases. If this could be prevented or reduced, considerable financial savings would result for the province.

AFBC/soil mixes are subject to expansion that under normal circumstances would be destructive and cause them to be excluded from use in highway construction. However, if controlled or limited expansion resulted from combined use of AFBC residues with Portland cement, then it is possible that sub-base shrinkage and the consequent reflection cracking of pavements could be prevented. Both the P.E.I. departments of Transportation and Public Works and Parks Canada (Atlantic Region) have expressed interest in this concept.

A number of tests were performed on the residues in combination with a soil from P.E.I.:

- grain size analyses (CSA A23.2-2A),
- standard Procter test (ASTM D698),
- harvard miniature compaction test,
- unconfined compressive strength,
- expansion (free),
- freeze-thaw durability.

Grain size

Data from grain size analyses of the residues and the soil used in the experiments are shown in Fig. 2 and 3. The following features are apparent from these data:

- The bed drain material is narrowly and continuously graded with 90% of the particles in the range 1.5 to 0.5 mm.
- The baghouse ash is composed predominantly of fine particules with 90% of the grains less than 0.1 mm in diameter.
- The silo ash material is bi-modally size distributed, suggesting that it was composed of almost equal parts of bed drain and baghouse ash.
- The soil is a poorly graded sandy-silt with some coarse gravel, little medium sand and an excess of fine particules. Atterberg limit tests classified the soil as non-plastic.

Compaction

Figure 4 shows the moisture density relationships for binary combinations of soil and either AFBC wastes or Portland cement. These data show that baghouse ash, either alone or as a component of the silo ash, increased the water demand and reduced the optimum density of compacted soil.

Strength development

Table 5 summarizes the data on strength development of the soil/cement/residue specimens. They were prepared at moisture contents close to those determined for optimum compacted density. After compaction the cylinders were sealed in plastic bags for curing at 23°C for 7 and 28 days.

The unconfined compressive strength of the soil alone was 0.13 MPa and 0.09 MPa at 7 and 28 days respectively. Addition of Portland cement (10% and 7.5%) clearly was beneficial with increases in strength at 7 and 28 days.

In the first experiments additions of both AFBC residue and Portland cement produced less strength gains than expected from the proportions of the materials. The mixes containing AFBC residues showed unexpectedly lower compressive strengths than those using Portland cement alone.

In subsequent experiments using silo ash it was established that this resulted from incomplete hydration of the Portland cement in the presence of

calcium sulphate (anhydrite) under conditions where moisture could not enter the system during curing. Table 6 presents the results for strength development of soil/cement/silo ash mixes where adequate moisture was available for complete curing.

Freeze-thaw durability

In most parts of the Atlantic Provinces, highway base structures are subject to numerous cycles of freezing and thawing during their useful life. Freeze-thaw durability is a critical requirement for practical use of a soil-cement mix in such circumstances.

The Portland Cement Association recommends that for adequate field durability, a soil-cement specimen should not lose more than 14% of material during 12 cycles of freezing and thawing in standard tests. The data from this study showed that this criterion was not met by the soil-cement mixes containing silo ash.

These observations are consistent with those reported by Minnick (5) for soil-ash mixes and are inconsistent with those of Nebgen et al. (7) on soil stabilization. The work reported by Minnick (5) was conducted using AFBC residue as a substitute for lime in the stabilization of two soils, a silty loam and a silty clay. Nebgen et al. (7) studied soils ranging from non-plastic silts to highly plastic clays. They found that except for montmorillonitic clay other types of soil responded well to the use of AFBC residue as a stabilizing aid. These observations would indicate that AFBC residues may be acceptable for stabilization or cementing of some soils.

Dimensional stability

Two series of tests were carried out using a free swell method for the determination of expansion. Table 7 shows the results from expansion measurements up to 30 h for four soil-cement-residue mixes.

The examination of dimensional stability was extended to measurements of four other mixes over a longer time. Table 8 shows the data from these experiments.

4.2.2 Compatibility of AFBC Wastes with Asphaltic Concretes

To evaluate the performance of AFBC wastes as fillers in asphaltic concrete mixes, a series of Marshall Mix Design experiments was conducted

using local materials. It was concluded that acceptable asphaltic concretes can be produced using AFBC residues from Summerside. However for a mix employing 10% bed drain material an optimum asphalt content of 6.25% must be used (compared with 6% for the normal mix). This mix requires an increase of 6% in the amount of imported sand and a reduction of 16% in the local sand. Such a mix would clearly not be economic.

Silo ash appears to be more encouraging. Using 5% silo ash, 26% of the imported sand could be replaced with an increase of 19% of local sand and 2% of imported stone. The resulting increase in surface area by the addition of silo ash increased the asphalt demand to 6.5%.

4.2.3 Compatibility with Portland Cement Systems

The objective of this part of the study was to establish whether the Summerside AFBC residues have value as components of construction materials based upon Portland cement binders. The criteria for evaluation are:

- The material must either be a pozzolan and thus reduce the requirement for Portland cement, or it must be an aggregate and reduce the need for natural sand, or it must bring to the product some other performance value.
- It must do one or more of the above without adversely influencing any of the desired properties of the normal Portland cement system.

The following were examined in laboratory studies:

- pozzolanic activity,
- set time,
- strength development,
- dimensional stability.

Pozzolanic properties

Standard tests found the Summerside residues not to be pozzolanic. This observation is consistent with the data in the literature and with the conclusions drawn on the basis of chemical properties.

In this regard they must be clearly distinguished from the residues from combustion of coal in pulverized fuel boilers, which in some cases are highly pozzolanic glasses.

Setting time

Mortars made using the Summerside residues showed some decrease in set time (determined by the Gilmore needle) compared with control mortars. No retardation or false-setting was observed.

Strength development and dimensional stability of test mortars

To evaluate strength development of Portland cement systems in the presence of AFBC residues, tests were conducted on mortars made in accordance with the ASTM C 109 procedure. It was noted that the incorporation of AFBC residues caused an increase in the water demand for equivalent workability.

Figure 5(a) shows the strength development of mortars containing bed drain as sand replacement. Comparison of the behaviour of the test and control mortars shows that the bed drain material had an adverse influence on compressive strength. Because only sand was replaced by the residue in these specimens, the reduction in strength must be attributed to one or more of the following:

- the bed drain residue is significantly weaker than the sand;
- it causes expansion and micro-cracking;
- the increased water demand causes excessive porosity in the cured mortars.

It is probable that all three effects contributed to the observed poor strength development. However, it should be noted that the loss of strength is much less severe than that observed with soil systems and cannot be interpreted as resulting from interference with the hydration of the Portland cement.

Figure 5(b) shows the strength development of mortars containing baghouse residue as a cement replacement. These data show that the material acts only as a diluent. There is no apparent disruptive activity but the residue contributes no cementing value.

As might be anticipated, the behaviour [Figure 5(c)] of the silo ash as part aggregate/part cement replacement is intermediate between the bed drain and the baghouse ash that are it's component parts.

The expansion data are consistent with these findings. Although expansion was observed with all of the materials, the mortars made with baghouse ash showed very little more expansive behaviour than the controls. Major dimensional changes were found for mortars incorporating bed drain material and silo ash. The source of the expansion is most probably the substantial volume change that occurs upon hydration of CaO and the lesser volume change associated with the formation of gypsum from anhydrite. This would be expected to be particularly destructive when the CaO is present in large particles. Some expansion may also originate with the formation of sulphoaluminates in the mortars.

5. CONCLUSIONS AND RECOMMENDATIONS FOR UTILIZATION OF AFBC WASTES

AFBC residues are unique among the products of coal combustion. Unlike pulverized fuel ash (fly ash) they are not solely composed of the elements contained in coal, nor are they pozzolanic glassy particulates. They resemble more the wastes produced by FGD systems except they are dry and contain lime and calcium sulphate in anhydrous forms.

Primarily they comprise heterogeneous particulate mixtures of CaO and $CaSO_4$ with minor and trace inclusions of the elements normally found in coal ashes and limestones.

From the point of view of disposal they present dust problems similar to fly ashes, potential for water pollution similar to FGD wastes and are additionally somewhat more caustic by virtue of their containing unhydrated lime.

From the viewpoint of utilization they present three classes of exploitable properties:

- potential sources of low grade lime;
- granular;
- somewhat cementitious (non-hydraulic).

Many uses have been proposed for AFBC residues in such industries as:

- agriculture - as a source of lime;
- pollution control - to neutralize and stabilize acidic and other liquid wastes;
- construction - as aggregate, lime substitute or cementing material.

It is concluded from this study that the heterogeneous nature, lack of pozzolanic properties and the elevated sulphate content of AFBC residues limit their application (especially in construction) to a few very specific potential uses. The most promising are:

- agriculture;
- lime substitute in acidic waste neutralization;
- waste stabilizing agent in lime/pozzolan systems;
- low strength backfill applications (with or without Portland cement);
- soil stabilization and soil cementing;
- asphaltic concrete aggregate.

Agriculture

Overall, if proven acceptable from environmental, health and plant growth perspectives the potentially most attractive application for AFBC wastes is in agriculture where lime and sulphate are both required for soil treatment.

Pollution control

In the field of pollution control AFBC residues offer two values. The lime content, although less than that of chemical lime, could be used to neutralize acidic wastes; the cementitious and water absorbing capacities of the residues could be used in the stabilization of sludges. Similar to agricultural applications, use in pollution control must be subject to environmental acceptability.

Aggregates

As aggregates for structural fill, AFBC residues have the advantage that they are moderately cementitious. However, they are also potential

sources of soluble sulphate therefore their use would be limited to circumstances where groundwater pollution or sulphate attack on surrounding structures are not at issue.

Cementitious applications

Previous investigators have sought to use AFBC residues in construction materials based upon Portland cement such as structural concrete and masonry block. The present authors consider these applications to be very much limited by the chemical and physical properties of the materials.

In terms of their compatibility with Portland cement systems, AFBC residues present a number of fundamental problems. Cement manufacturers take great care to limit the quantity of free lime in their product because in concrete the hydration of CaO that occurs some time after hardening of the mass causes dimensional instability and cracking. Similarly the sulphate content is limited in cement to prevent interference with setting.

Experimental examination of the Summerside residues and reported investigations by others confirm that Portland cement-based materials containing AFBC residues are subject to severe dimensional instability and lack of structural integrity. Thus it is expected that only under exceptional circumstances would a material such as AFBC residue be used as a concrete component. Such circumstances might be where expansion of the material was desirable (for example in a grout), or where dimensional stability was not important, such as in low strength backfill applications.

Soil modification and stabilization

In soil modification and soil cementing applications the same dimensional instability has been noted when unconditioned AFBC residues are used. In general applications this behaviour would preclude their use, however under circumstances where soil shrinkage is a problem AFBC wastes may be used to advantage. The major disadvantage in this application would appear to be the poor performance under freezing and thawing conditions of soils stabilized with AFBC residues.

Asphaltic concrete

The objections that may limit applications in cement based systems do not apply to the use of AFBC residue in asphaltic paving. Expansion of

the residue on aging should be less destructive than in an application such as concrete where a brittle solid is formed. Leaching to the immediate surroundings is unlikely to occur and sulphate attack on the binder matrix will not be an issue as it is for cementitious applications.

Experimental examinations of a limited range of asphaltic concrete materials using Summerside residues indicated no particular technical advantages or disadvantages. Their selection as asphaltic concrete aggregates will depend largely on the economics of transportation. It is perhaps worth noting that a 100 m test section of road at CFB Summerside was covered with asphalt employing a 3% silo ash mix in 1983 and at the time of writing (June 86) the section is still in good condition and shows no signs of deterioration (32).

6. ACKNOWLEDGEMENT

We wish to acknowledge the financial support of the Coal Division, Conservation and Alternative Energy Branch for two studies on AFBC Waste Evaluation upon which much of this paper is based and the award of a visiting fellowship to D.P. Kalmanovitch during the course of this work from the National Science and Energy Council of Canada.

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Table 1 - Chemical analyses of Summerside AFBC residues

Element	Concentration (ppm)	
	Bed drain	Baghouse Ash
Aluminum	14200	30900
Arsenic	310	220
Barium	154	213
Beryllium	0.10	<.09
Boron	24.6	63.1
Cadmium	1	15
Calcium	448000	299000
Chromium	10	23
Cobalt	5	5
Copper	7.7	29.4
Iron	16500	75900
Lead	45	140
Lithium	8	30
Magnesium	5350	9030
Manganese	849	635
Molybdenum	20	20
Nickel	27	47
Phosphorus	290	650
Potassium	2800	5500
Silicon	30900	54800
Silver	5	5
Sodium	1300	2100
Strontium	123	60.1
Titanium	574	1090
Vanadium	8.8	37.5
Zinc	209	343
Zirconium	20	24

From reference 22

Table 2 - Total sulphur content and calculated anhydrite contents of Summerside AFBC residues

Material	Total S (%)	Approx. % $CaSO_4$
Bed drain	11.46	48.7
Baghouse ash	6.89	29.3

Table 3 - Relative alkali activity of lime and Summerside AFBC residues

Type of alkali	Equivalent weight of sulphuric acid 100 g of alkali	Per cent activity relative to CaO
CaO	175.0	100.0
Bed drain*	15.8	9.0
Baghouse ash*	16.9	9.6
Bed drain**	71.1	40.6
Baghouse ash**	59.3	33.9

*Determined by ASTM C 400-64 (Hardy Associates)

**Data from reference 22

Table 4 - Calculated phase composition of Summerside AFBC residues

Material	CaO	$CaSO_4$	Other
Bed drain	40.6	48.7	10.7
Baghouse	33.6	29.3	37.1

Table 5 - Strength development of soil cements based on AFBC residues

Material	Age (days)	Unconfined compressive strength (MPa)
Series 1:		
Soil	7	0.13
	28	0.09
Soil + 10% PC	7	4.03
	28	4.19
Soil + 10% SA	7	0.32
	28	0.41
Soil + 10% BD	7	0.26
	28	0.30
Soil + 7.5% PC	7	2.28
	28	2.04
Soil + 7.5% PC + 7.5% SA	7	0.80
	28	1.46
Soil + 7.5% PC + 7.5% BD	7	0.70
	28	0.53
Soil + 10% PC + 10% SA	7	0.85
	28	1.75
Soil + 10% PC + 10% BD	7	0.74
	28	1.13

PC = Portland cement; SA = Silo ash; BD = Bed drain

Table 6 - Strength development of soil/cement/silo ash mixes with adequate moisture during curing

Material	Age	Unconfined compressive strength (MPa)
Series 2:		
Soil + 7.5% PC	28	2.25
Soil + 7.5% PC + 7.5% SA	28	2.12
Soil + 7.5% SA	28	0.30

PC = Portland cement; SA = Silo ash

Table 7 - Dimensional changes of soil cements up to 30 h

Material	Expansion (%)
Soil + 5% SA + 5% PC	0.8
Soil + 10% SA + 10% PC	-2.5
Soil + 5% BD + 5% PC	1.1
Soil + 10% BD + 10% PC	2.1

PC = Portland cement; SA = Silo ash; BD = Bed drain

Table 8 - Dimensional stability of soil cements up to 3 d

Time (mins)	1	2	4	8	15	30	60	120	240	4320
	Per cent expansion (+) or contraction (-)									
Mix No.										
1	0	0	0	0	(+) 0.02	(+) 0.05	(+) 0.05	(+) 0.08	(+) 0.09	(+) 0.12
2	0	(-) 0.02	0	0	0	(+) 0.04	(+) 0.08	(+) 0.10	(+) 0.40	(+) 0.30
3	(-) 0.05	(-) 0.07	(-) 0.08	(-) 0.10	(-) 0.03	(+) 0.10	(+) 0.25	(+) 0.32	-	(+) 1.8
4	0	0	(+) 0.02	(+) 0.08	(+) 0.10	(+) 0.20	(+) 0.25	(+) 0.40	-	(+) 2.17

Key:	Materials	Mix No.
	Soil + 7.5% PC	1
	Soil + 7.5% SA	2
	Soil + 7.5% SA + 7.5% PC	3
	Soil + 7.5% BD + 7.5% PC	4

PC = Portland cement; SA = Silo ash; BD = Bed drain

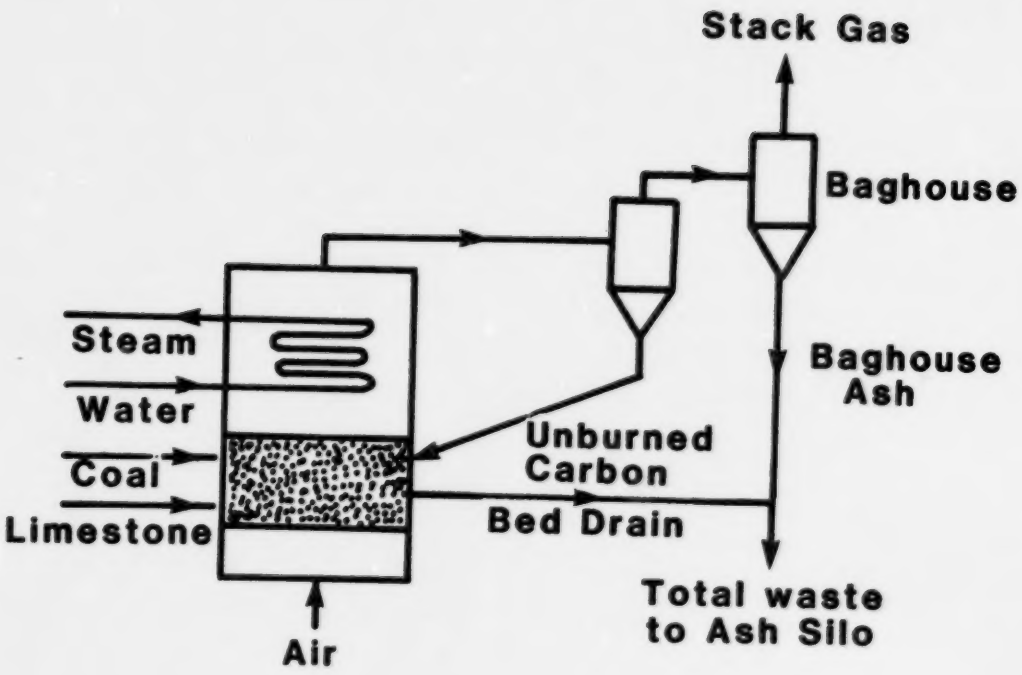

Fig. 1 - Typical material flow in a fluidized bed combustion system

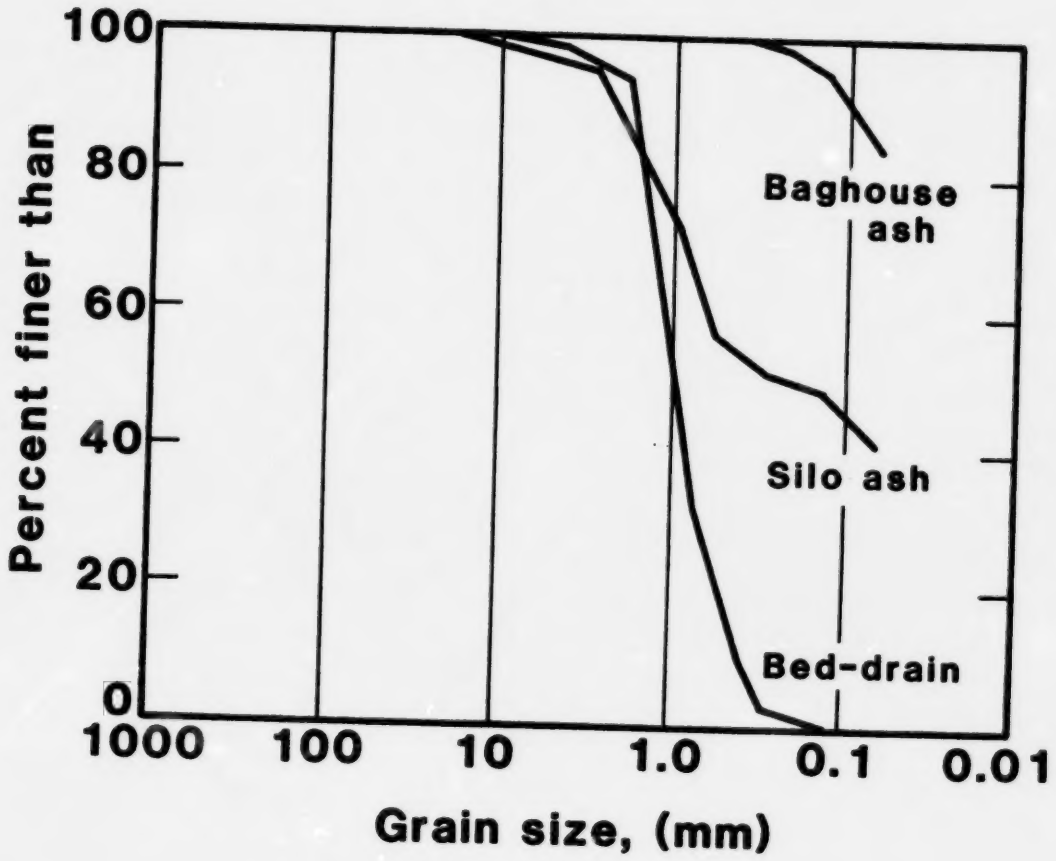

Fig. 2 - Grain size distributions of AFBC residues

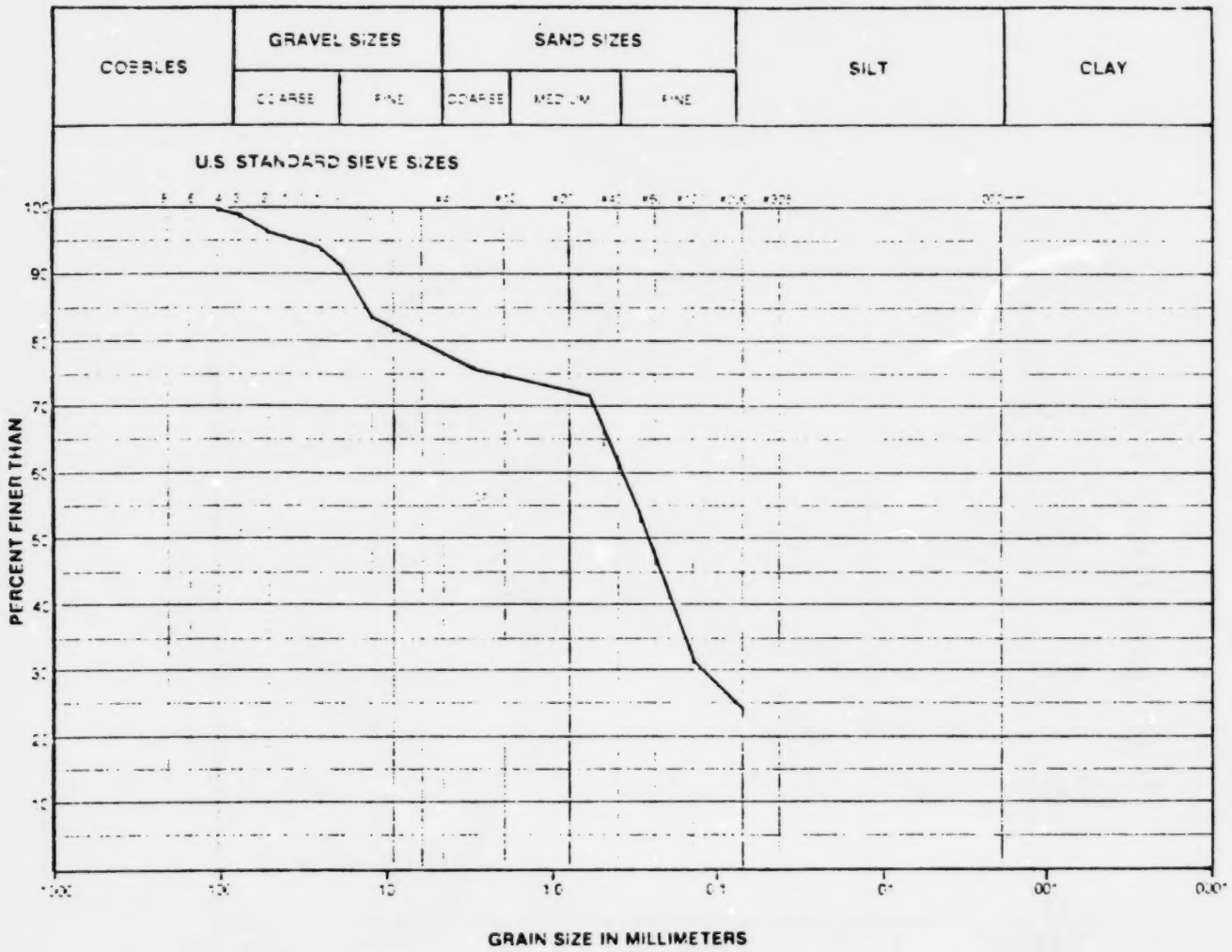

Fig. 3 - Grain size distribution of P.E.I. soil

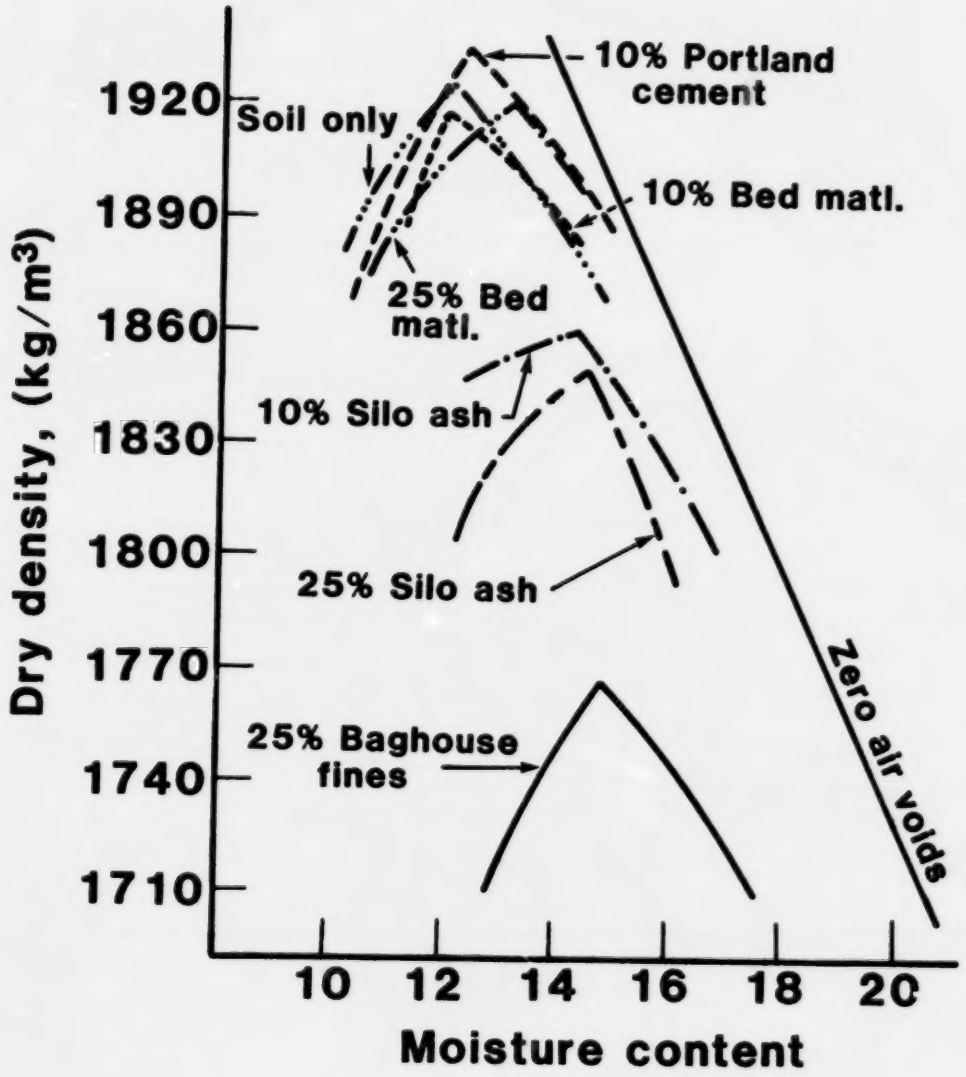

Fig. 4 - Moisture-density relationship of soil/AFBC residue/Portland cement combinations

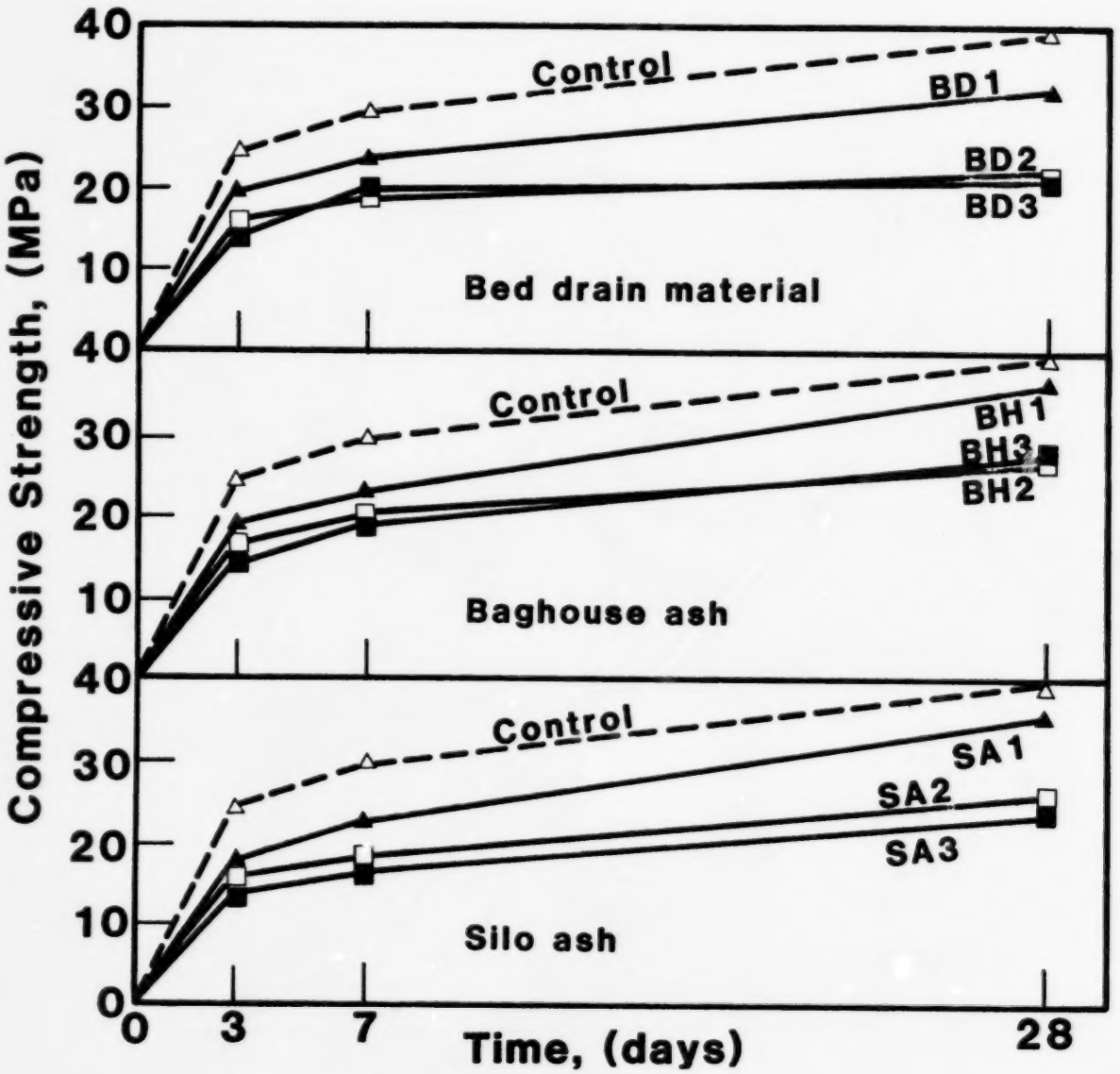

Fig. 5 - Strength development of Portland cement mortars containing AFBC residues

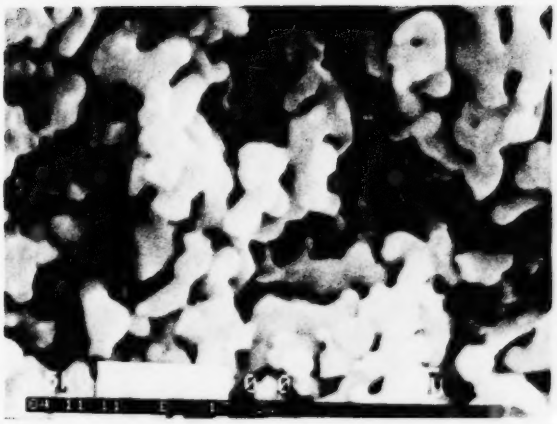

Plate 1 - Porous calcined region of limestone bed sample. (No Sulphur was detected). Bar = 10 µm.

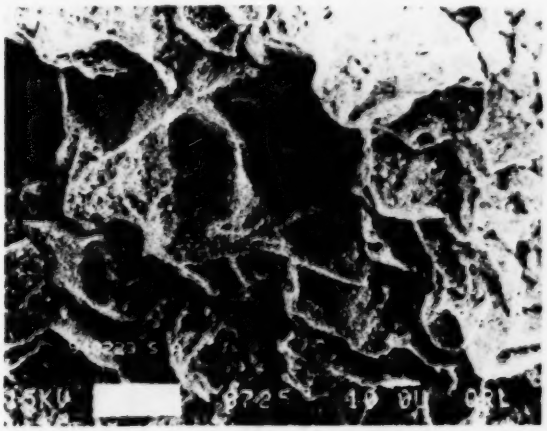

Plate 2 - Relatively non-porous sulphated region of limestone bed samples. Cracks were probably due to fracturing of particle for topographical observation. Ca and S only present. Bar = 10 µm.

Plate 3 - Overall view of bed material from the Summerside boiler. Large coal mineral particles (dark grey) can be seen. The inner calcined region was "picked out" during polishing leaving the sulphate rim. Note the relatively symmetric rim and cracks in the particle. Bar = 1 mm.

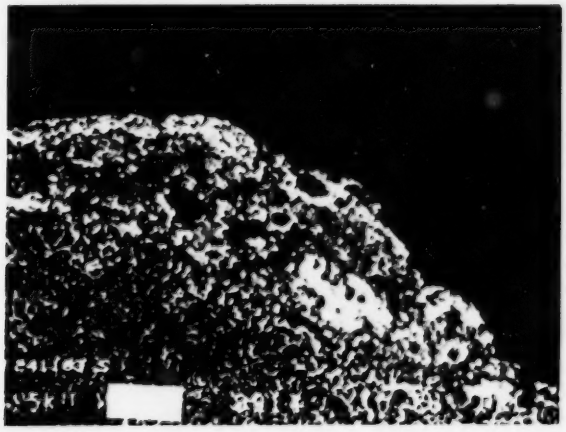

Plate 4 - Details of ash rich skin or limestone particles about 15-20 µm thick. The skin is rich in Fe, Al, Si and Ca but relatively low in S. Apart from Fe inclusions the skin appears homogeneous indicating a phase had formed as a product of reaction. Bar = 10 µm.

Plate 5 - Particle exposed to the atmosphere for a sufficiently long time to observe hydration effects. The structure clearly indicates hydration of CaO and an increase of volume leading to cracking and fragmentation of the bed particle. Bar = 1 mm.

Plate 6 - Project engineer at CFB Summerside standing on a boulder formed by weathering of FBC waste material at CFB Summerside.

Plate 7 - Crust-thickness formed by the weathering of FBC waste material from CFB Summerside.

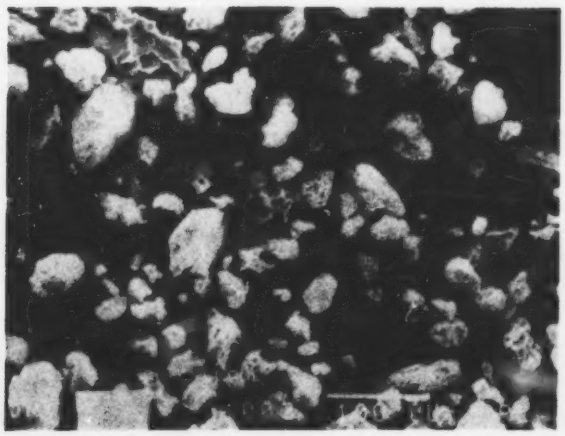

Plate 8 - Cyclone material. Bar = 100 µm.

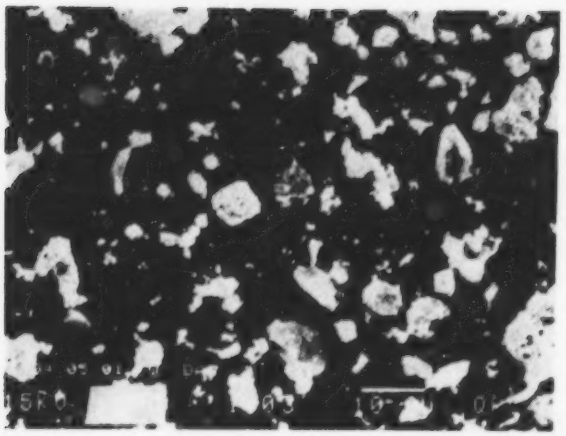

Plate 9 - Baghouse material. Bar = 10 µm.

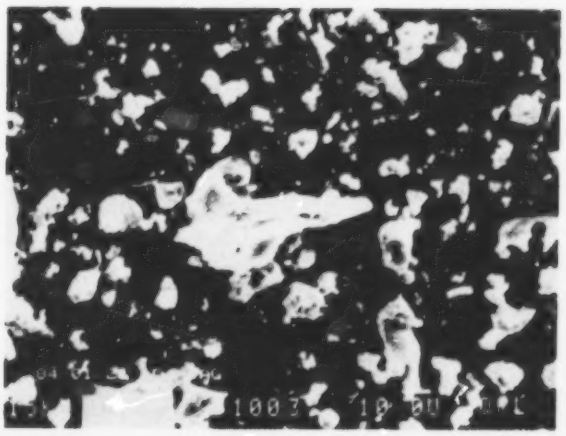

Plate 10 - Baghouse material. Bar = 10 µm.

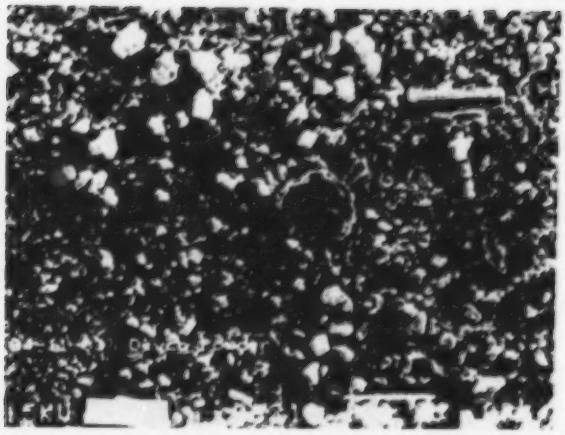

Plate 11 - Elutriated material prior to mixing with the bed material and discharge to the silo. Bar = 10 µm.